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A new technique to estimate regional irrigation water demand and driving factor effects using an improved SWAT model with LMDI factor decomposition in an arid basin

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ABSTRACT

To figure out the driving factors of irrigation water demand and an effective way for relieving the sharp contradiction between the supply and demand of agriculture water resources in the Heihe River basin of Northwest China, a conventional method in estimating irrigation water demand was modified by incorporating the simulations of Soil and Water Assessment Tool (SWAT) model with its distributed hydrological response units (HRUs). Simultaneously, a new factor decomposition model for irrigation water demand was created using the extended Kaya identity. Moreover, the additive and multiplicative forms of the logarithmic mean Divisia index (LMDI) decomposition were used to quantify the variation of driving factors in irrigation water demand from 1985 to 2014. The results show that total irrigation water demand in this arid region had increased by 3.249×10^8 m^3 over the past 30 years. These contributions are arising from the following four driving factors - planting scale, planting pattern, climate change and water saving technology (e.g., drip irrigation, sprinkler irrigation, etc.) with respective contribution of irrigation water demand of 1.981×10^8 m^3, 0.933×10^8 m^3, 1.523×10^8 m^3 and -1.188×10^8 m^3. The corresponding average contribution rates of these driving factors are 60.96%, 28.72%, 46.86% and −36.53%, respectively. Although the effects of the four drivers on the irrigation water demand for various crops over three periods (i.e., 1985–1994; 1995–2004; 2005–2014) are inconsistent, both the planting scale and the cropping pattern increase the irrigation water demand. Water saving technologies as known have inhibited water demand, but climate change turns out to increase the demand and then inhibit it. Therefore, to reduce the irrigation water demand and develop a proper irrigation water planning in Heihe River basin, it is beneficial to regulate the scale of agricultural development, adjust the agriculture pattern by reducing the area planted with crops that consume relatively large amounts of water (i.e. spring corn and vegetables), identify agricultural water saving potential and decrease the impact of climate change.

1. Introduction

China is one of the most water-scarce countries in the world. Limited water resources heavily constrain China's economic and social development (Cheng et al., 2009; Guo and Shen, 2016; Kang et al., 2017; Shen et al., 2013), especially in the country's arid and semi-arid regions (Du et al., 2015; Ma et al., 2012; Vorosmarty et al., 2000). Within agriculture (China's biggest water consumer), the irrigation accounts for about 90% of agricultural water use (Kang et al., 2017). The agricultural water shortage may be intensified due to continuing economic development, rapid population increase and the impact of global climate change (Du et al., 2015; Kang et al., 2017).

The demand for irrigation water is mainly influenced by climate change, the scale and patterns of crop planting, and the use of water saving technologies. Climate change affects the demand for irrigation by altering crop water demand. Appropriate planting scale and planting patterns can effectively reduce irrigation water demand. Water saving technology such as drip irrigation can provide efficient irrigation equipment and thus improve the efficiency of irrigation methods to reduce irrigation water demand (Xie and Su, 2017). Tillage and cultivation practices, such as the use of plastic film mulch, can prevent irrigation water from losing (Kang et al.,

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2017). Due to the deficit of irrigation water and the limited existing water resources, an effective way to reduce irrigation water demand is urgent. Therefore, exploring the factors that influence the irrigation water demand, and quantifying their contribution to that demand could provide insights on controlling the scale of agriculture. Moreover, this can improve agricultural water conservation practices and promote more sustainable agriculture to secure food production in China.

Demand for irrigation water is determined by factors such as net irrigation water demand, planting practices, regional crop selections and the efficiency of irrigation water use (Shen et al., 2013; Wu and Chen, 2013). Net irrigation water demand is closely related to the water demand of a crop and the need for an effective supply of water during the crop growth period. Conventional methods to estimate effective water supply are based on the relationship between monthly mean precipitation and monthly crop water demand, neglecting the effects of the infiltration rate and the precipitation intensity (Wu and Chen, 2013). When the infiltration rate is low, and precipitation intensity is high, a considerable amount of water may be lost through surface streamflow (runoff), which was not considered by Doorenbos and Pruitt (1977). Seepage from the root zone and subsurface lateral flow can also result in water loss, which was not reported by Doorenbos and Pruitt (1977). These components of the hydrological process can be monitored by a distributed hydrological model to accurately calculate effective precipitation.

The Soil and Water Assessment Tool (SWAT) is a distributed hydrological model that has been widely used in hydrologic cycle models (Arnold et al., 1998). There have been many studies on irrigation water demand for single crops (Chung et al., 2011; Liu et al., 2013), but aggregate total regional irrigation water demand has not been comprehensively modeled. We incorporate the attributes of the distributed hydrological response calculation units in SWAT, taking advantage of its distributed crop water demand calculation and the accuracy of effective precipitation calculation, to estimate the change in irrigation water demand for each crop (i.e., spatially) and the total irrigation water demand for the crop growth period (i.e., temporally). Many published studies also reported the relationship between irrigation water demand and the influencing factors. Hu et al. (2014) found that effective precipitation was a significant predictor of irrigation water demand for winter wheat in Northern China by analyzing correlations between meteorological factors and irrigation water demand. By using multivariate linear regression analysis, Ma et al. (2011) concluded that the main driving factors of irrigation water demand were the wheat and vegetable acreages in the North China Plain. Ma et al. (2012) created an agricultural net irrigation water model by analyzing the correlation between net agricultural irrigation water demand and its macroscopic driving factors (such as population, urbanization rate, irrigated area, and natural precipitation) in the Shiyang River basin. However, these studies mainly focus on the correlation between irrigation water demand and the factors that influence it, not quantifying in what magnitude they matter to irrigation. It is necessary to examine the quantity or contribution ratio of these factors to irrigation water demand.

To date, there have been developments in methods for the quantitative analysis of factors that influence the use of water resources. Of particular interest are principal component analysis, factor analysis, artificial neural network analysis, factor decomposition, and suchlike. Ang et al. (1998) used the factor decomposition method to analyze the extent of the influence of different driving factors. Note that index decomposition analysis (IDA) is a form of factor decomposition such as Laspeyres index decomposition or Divisia index decomposition that has been commonly used. There are two interrelated forms of decomposition (additive and multiplicative) which can improve both the temporal and spatial analysis of factor variables (Xu et al., 2015; Zhang et al., 2016c). Based on Divisia index decomposition, Ang (2015) developed the logarithmic mean Divisia index (LMDI) method which has been widely used in the fields of environmental economy and energy consumption (Chong et al., 2015; Lei et al., 2012; Tursun et al., 2015). Note that LMDI decomposition effectively deals with the problem of a residual in the decomposition process and provides the logarithmic average weight equation. It also provides the advantage of using quantitative indicators and intensity indicators. Because of its flexibility, LMDI decomposition has recently been used in the management of water resources. For example, Zhao and Chen (2014) investigated the driving factors of China's agricultural water usage by LMDI decomposition and concluded that economic benefits are the most important factor that can increase water usage in China. Zhang et al. (2014) used LMDI decomposition to analyze industrial water use in the Anhui province by quantifying the water consumption of different industrial sectors and total water use. Zhang et al. (2015c) used LMDI decomposition to investigate the water resource utilization in Urumqi. They calculated the relative contribution rate of each driving factor and found that the main determiners of water demand are the level of economic development, water use efficiency, industrial water distribution methods, industrial development, and the efficiency of industrial water use. Although LMDI decomposition has been used to analyze the water resource utilization, little research is found on its application to quantify and analyze the driving factors of irrigation water demand in arid areas.

Water shortage limits socio-economic development and could cause serious ecological and environmental damage in the arid inland area of the Heihe River basin. Agricultural water consumption accounts for up to 80% of total water consumption in the region (Li et al., 2016). The processes that cause change in the demand for irrigation water in the Heihe River basin are identified in this study. Whether the current agricultural development model is effective in reducing demand for irrigation water is also evaluated, which provides a basis for promoting the health of agricultural development in the region. The main objectives of this study are: (1) to construct a regional SWAT model and modify the conventional method in estimating irrigation water demand by incorporating the simulations of SWAT with its distributed hydrological response units (HRUs) to improve the estimation of irrigation water demand on a regional scale; (2) to quantify the temporal and spatial distribution of irrigation water demand for crops in the study area from 1985 to 2014; (3) to create a decomposition model of four factors for irrigation water demand (planting scale, planting pattern, climate change and water saving technology) by using the extended Kaya identity and LMDI decomposition in order to quantify and evaluate the contribution rate of each factor; and (4) to evaluate and discuss how the key factors that drive change in irrigation water demand might be varied in order to reduce demand.

2. Study area

The Heihe River basin is a typical inland river basin in Northwest China, located in the middle of Hexi Corridor and the Qilian mountains, across Qinghai, Gansu and Inner Mongolia provinces (from south to north). The study area comprises the middle and upper reaches of the Heihe River basin, from the source of the Heihe River (in the Qilian mountains) to Zhengyixia (Fig. 1). The upper reach of the Heihe River is in the south of the Qilian mountains, at altitudes of 1680 m–5280 m and covers an area of 10 009 km^2. The middle reach of the Heihe River is located between Yingluoxia and Zhengyixia, at altitudes of 1300 m–1660 m and